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COSMIC-RAY HEAVY NUCLEI AT GEOMAGNETIC LATITUDE 42°N*

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The flux of primary cosmic ray heavy nuclei has been measured with a sandwich of C.2 and G.5 emulsions near the coast of Georgia, magnetic latitude 42°N. The emlusions were exposed at about 122 000 ft for 7.5 hours and the calculated fluxes at the top of the atmosphere in particles/m^2-sec-sr were found to be:

Li, Be, B	(L nuclei)	1.15 ± 0.3
C, N, O, F	(M nuclei)	3.97 ± 0.4
$Z \gtrsim 10$	(H nuclei)	1.29 ± 0.3

This flight took place on May 25, 1960, near sun spot maximum. Evidence of solar modulation of the primary cosmic ray flux is shown.

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INTRODUCTION

The primary cosmic ray spectrum has been measured by various investigators at geomagnetic latitudes near 41°N and magnetic rigidity $R > 4.5$ BV. Summaries of the charge distribution and fluxes for nuclei of $Z \geq 3$ have been presented for groups of nuclei commonly designated L (Z=3,4,5), M (Z=6,7,8,9), and H ($Z \geq 10$).[1-3] Discrepancies in measured flux values are largely due to experimental difficulties in obtaining clear-cut charge resolution, uncertainly in corrections required in the extrapolation of the data to the top of the atmosphere, and due to a time dependence associated with solar activity.[4]

In this work the charge distribution and flux values for L, M and H nuclei were obtained at an altitude of 122 000 $\pm$ 2000 feet (3.9 gm/cm^2 residual atmosphere), which is sufficiently high to materially reduce the corrections for atmospheric attenuation and for the production of L nuclei due to fragmentation of M and H nuclei in the upper atmosphere. The flight date was May 25, 1960, approximately 2 years after the solar maximum and well within the most recent period of minimum cosmic ray activity. A total flux of 6.4 ± 0.4 nuclei/m^2-sec-sr was obtained. This result is lower than any previously reported. It will be discussed in relationship to the solar cycle and measurements on the time variation of primary cosmic rays.

EXPERIMENTAL PROCEDURE

A. Emulsion Stack

The emulsion stack flown in this experiment consisted of 14 type G.5 Ilford stripped emulsions 8 x 8 inches, 400 microns thick, alternated with 13 type C.2 emulsions, 200 microns thick. The plane of the emulsions was maintained vertical in a masonite and cardboard container with wall thickness 0.38 gm/cm^2.

The G.5 emulsions were processed in a conventional manner for 40 minutes at 21.5°C in a standard Amidol developer after being mounted on glass, presoaked in water for 120 minutes at 4° C and soaked in developer for 90 minutes at 4°C. In order to reduce background fogging, the C.2 emulsions were developed for 80 minutes at 3.6°C in 70% normal strength Amidol. This low temperature resulted in severe underdevelopment so that only tracks of $Z > 6$ could be easily located and grain counted.

B. Exposure

The emulsion stack was exposed in a free balloon flight (Winzen Research, Inc., Skyhook Glynco, Flight No. 869) near Brunswick, Georgia, on May 25, 1960. The rise time from sea level to 122 000 ± 2000 feet was 2.0 hours. Flight time was 7.5 hours at 122 000 feet; residual atmosphere 3.9 gm/cm^2. Time of descent was 0.5 hours (see figures 4 and 5).

The entire flight was made at a geographic latitude of 31° ± 0.3° North or a geomagnetic latitude 42° ± 0.3° North. Longitude reading varied from 81° W to 84° W. The data of this experiment will be compared to other work carried out at geomagnetic latitude = 41° N and magnetic rigidity $R > 4.5$ BV.

C. Scanning Technique

The second G.5 emulsion from the edge of the stack was chosen for scanning. The plate was divided into four 4 x 4 inch squares and each was scanned to within 0.5 cm of the outer edges. Relativistic proton and alpha particle tracks in high energy jets were countered to obtain the grain density ($\approx$18 grains/100 microns) for minimum ionization tracks. All tracks having over six times this grain density and a dip angle less than 33.7° were recorded and followed through at least 15 emulsions. Only tracks with dip angle less than 21.5° were finally used in the flux determinations. Tracks were assumed to be due to relativistic primaries if multiple scattering was unobservable and if they could be followed for at least 16.4 mm with a negligible change in track density and an angular deviation less than 2°.

Two groups of scanners worked independently. One group observed 27.8 tracks/cm^2 and the other 28.0 tracks/cm^2 for tracks with dip angle $0° \leq \beta \leq 21.5°$ and zenith angle $0° \leq \theta \leq 70°$. Scanning efficiencies of 90% for L nuclei and 95% for M and H nuclei were estimated by rescanning 15% of the plate area.

D. Charge Calibration

G.5 grain counts of relativistic protons and alpha particles were 18 ± 4 and 70 ± 8 grains/100 microns, respectively. Tracks of Z = 3 counted 140 $\pm$ 20 grains/100 microns. Grain density saturation made it difficult to resolve tracks of $Z = 3$, 4, and 5 by means of grain density measurements. Hence G.5 gap count was used to classify tracks in the range $4 \leq Z \leq 10$ and grain count in underdeveloped C.2 plates was used for tracks of $Z > 6$. Both criteria were used in the range of $6 < Z \leq 10$.

Charge calibration of the grain and gap counts was based on six high energy fragmentation events in which the product tracks were grain counted in G.5 emulsions and identified as alphas and protons. Although the individual charge determining events were not entirely self consistent, they were used collectively to assign the cutoff point between charges 5 and 6 at gap counts of 19/100 microns for tracks with dip angle $14^\circ < \beta \leq 21.5^\circ$ and at 22/100 microns for tracks with dip angle $\beta \leq 14^\circ$, respectively. Assuming a Z^2 dependence for C.2 grain counts it was possible to assign a cutoff value for charges $Z \gtrsim 10$ at 27 grains/100 microns.

CHARGE DISTRIBUTION

The detailed charge spectrum determined from the data of this experiment is subject to uncertainty since gap counts were the only criterion for the charge assignment for most of the $Z = 5$ and $Z = 6$ tracks. Both gap and grain counts were made on some $Z = 6$ tracks and on most of the $Z = 7$, 8, 9, and 10 tracks. Above $Z = 9$ only C.2 grain counts were used. The gross spectrum of L, M and H nuclei and the corresponding absolute flux values are much more reliable.

Figure 1 presents a histogram of the number of tracks observed by one group at flight altitude, versus the C.2 grain count. This graph includes tracks with dip angle $\beta \leq 33.7°$ and zenith angle $\theta \leq 70°$. The low end of the histogram is not a true representation since many Z = 6 and some Z = 7 tracks were not counted in the C.2 plates. The C.2 calibration shown on this graph was determined from the high energy fragmentation events.

Figure 2 presents histograms of the number of tracks at flight altitude versus gap count for tracks grouped according to dip angle $0° < \beta \leq 14°$ and $14° < \beta \leq 21.5°$. Three features are evident: 1. The charge distribution for $Z \geq 6$ is smoothed out due to low counting statistics and crowding at low gap count. 2. The peaking at Z = 7 is due to the statistical spread in gap counts for tracks of Z = 6 and 8. 3. For the steeper tracks the peaks are shifted to shorter gap count values. We attribute this to the facts that for steep tracks some very narrow gaps will be missed and that the number of missing grains in wider gaps estimated along the horizontal will be less than the actual number along the track.

From the combined data of Figures 1 and 2 and similar data taken by a second group a charge value was assigned to each track. The resulting histogram, showing the weighted number of tracks at flight altitude for each Z value, is presented in Figure 3. This histogram includes only tracks with $0° < \beta \leq 21.5°$ and $0° < \theta \leq 70°$.

FLUX DETERMINATION

The flux of primary cosmic ray heavy nuclei at the top of the atmosphere was determined by restricting analysis to dip angles $0^\circ < \beta \leq 21.5^\circ$ and zenith angles $0^\circ < \theta \leq 70^\circ$ for M and H nuclei and $0^\circ < \theta \leq 60^\circ$ for L nuclei. The flux calculation was carried out by the method of Bradt and Peters as reported previously in a study carried out at 3°N.[5] A three step numerical integration was performed over the separate intervals: rise time, flight time, and descent time. Each track was weighted and the number of tracks observed was thereby increased to account for absorption in the packing material and in the emulsion. This correction also accounted for those tracks that were scanned but not included, because they interacted in the emulsion before going the required distance. The correction for absorption in air was made as a function of zenith angle and incorporated into the numerical integration over the zenith angle range. Absorption mean free paths used were 33, 30, and 22 gm/cm^2 for L, M, and H nuclei, respectively.

The number of L nuclei was reduced to account for fragmentation of H and M nuclei in the atmosphere. Fragmentation probabilities $P_{HL}=P_{ML}=0.25$ were used. This correction was sufficiently small so that it was relatively insensitive to uncertainities in P_{HL} and P_{ML}. A correction factor of 10% was made for tracks which passed out of the stack before penetrating 15 emulsions by comparing the track density at the center of the plate and at various distances from the edge.

Flux values in nuclei/m^2-sec-sr corrected to the top of the atmosphere were:

J_L = 1.15 ± 0.3 ...... $17.9\% \pm 5\%$

J_M = 3.97 ± 0.4 ...... $61.9\% \pm 6\%$

J_H = 1.29 ± 0.3 ...... $20.2\% \pm 5\%$

Total flux $J = 6.41 \pm 0.4$.

DISCUSSION OF RESULTS

The relative abundance of the heavy nuclei ($Z \geq 3$) in primary cosmic radiation above 4.5 BV and the flux values obtained by other workers have been summarized in the review articles by Waddington,[3,6,7] and by O'Dell, Shapiro and Stiller.[8]

A. Charge Spectrum

The charge spectrum at 3.9 gm/cm^2 residual atmosphere is presented in Figure 3 using only those tracks with dip angle $0° < \beta \leq 21.5°$ and zenith angle $0° < \theta \leq 70°$. Statistical fluctuations in grain and gap counts result in low resolution and tend to smooth out the charge spectrum. This accounts for the fact that the values at Z = 4, 7, and 9 are somewhat higher than would be expected. Since the calibration for Z = 8 is based on an extrapolation of C.2 grain count data, the spectrum is shown only up to Z = 10.

The percent abundances of the nuclei are presented in Table I, where they are compared with those of other workers. Our percentages are in essential agreement with the previous work since the abundances of L nuclei decrease when corrected to the top of the atmosphere, and the abundance of H nuclei increases slightly. The % values for Z = 9 and Z = 10 are very sensitive to the chosen cutoff in C.2 grain count. The value for Z = 9 has an estimated standard error of 50%. The percentage of nuclei of Z = 10 is lower than that quoted by Waddington[3] but within the estimated error of $(19.5 \pm 4.0)\%$. This suggests that the solar modulation of the heavy flux is at least as great as for the lighter primary nuclei.

Table I. Percentages of primary nuclei of magnetic rigidity R>4.5 BV.

Z	O'Dell et. al.[a] $\chi=0$[b]	Waddington[c] (Mean Values) $\chi=0$	Present Work $\chi=3.9$	$\chi=0$
3	5.3	3.9	3.3	
4	2.3	1.7	4.9	
5	7.4	11.6	12.4	17.9
6	30.1	26.0	18.2	
7	9.7	12.4	15.8	61.9
8	19.4	17.9	20.2	
9	2.4	2.6	6.1	
≥10	23.4	23.9	19.1	20.2

a See reference 8.
b χ is the amount of atmosphere traveresed in gm/cm^2.
c See reference 7.

B. Flux Ratios

Although the total flux measured in this experiment is low, the L/S and H/M flux ratios shown in Table II agree within the experimental limits of error with those quoted as best values by Waddington.[3,7] The H/M ratio is lower than that reported by O'Dell, et al,[8] but the difference is not statistically significant.

Table II. Flux ratios at flight altitude and at the top of the atmosphere.

	Waddington[a] Best Values $x = 0$	O'Dell, Shapiro and Stiller $x = 0$	Present Work	
			$x = 3.9$ gm/cm^2	$x = 0$
L/S	0.21 ± 0.05	0.18 ± 0.04	0.26 ± 0.06	0.22 ± 0.06
H/M	0.34 ± 0.04	0.38 ± 0.04	0.32 ± 0.07	0.33 ± 0.07

a See references 3 and 7.

C. Solar Modulation of Primary Cosmic Ray Flux

The absolute flux values obtained in this experiment are significantly lower than those reported by other observers. In order to explain our low value of total flux, $J = 6.41 \pm 0.40$ nuclei/m^2-sec-sr, we must consider the time of the flight, May 25, 1960, in relationship to the solar activity cycle and to the results of other workers obtained at different times.

Many investigators have shown the inverse relationship between cosmic ray intensity and solar activity.[1,4,7,9-12] Webber[4] has shown that $Z \geq 6$ nuclei participate in the same manner as protons and alpha particles and that the effect may be measured by cosmic ray neutron monitor data. Although lower rigidity particles are affected most, the modulation extends at least to a magnetic rigidity of 25 BV. Neher[10,11] has shown that the recent minimum in the cosmic ray ionization curve extended well into the summer of 1960 and that the cosmic ray minimum seems to lag behind the sun spot maximum by from 9 to 12 months.

Webber[4] has compared the particle flux values for protons, alphas and M + H ($Z \gtrsim 6$) nuclei with magnetic rigidity $R > 4.5$ BV with the Mt. Washington neutron count rate. The mean hourly count rate at solar minimum ($\approx$1954) is taken as 2506. The monthly average for May, 1960 was 2023, and the daily average for May 25, 1960 was 2025. Using the neutron ratio 2025/2506 we find from Webber's summary that a factor of 1.40 ± 0.05 should be applied to correct flux values J_s for meduim and heavy nuclei, to solar minimum. The corresponding factor for alpha particles and protons is 1.36. Because these factors are based on measurements made by many observers, the statistical fluctuations are large and we cannot regard them as significantly different.

Table III. Flux values adjusted to the mean cosmic ray level near solar minimum (≈1954).[a]

	This Work May 25, 1960	This Work Adjusted to Solar Minimum	Mean Values of Four Observers Adjusted to Solar Minimum[b]	Adjusted Best Values According To Waddington[b]
J_L	1.15 ± 0.3	1.61 ± 0.4	2.06 ± 0.17	1.60 ± 0.40
J_M	3.97 ± 0.4	5.56 ± 0.6	5.70 ± 0.28	5.70 ± 0.28
J_H	1.29 ± 0.3	1.80 ± 0.4	2.17 ± 0.18	1.94 ± 0.25
J	6.41 ± 0.6	8.97 ± 0.8	9.93 ± 0.37	9.24 ± 0.55

a Correction factor based on Mt. Washington neutron monitor levels correlated with flux values for meduim and heavy nuclei of rigidity 4.5 BV by Webber.[4]

b See reference 7.

Our flux values, adjusted by the factor 1.40, are presented in Table III where they are compared with the mean value of four other observers[7] and with the adjusted "best values", according to Waddington.[7]

The standard errors in our data are comparable to those of other experiments but greater than those quoted for mean values. The measured heavy flux, $J_H = 1.29 \pm 0.3$, agrees with the value obtained by Neelakantan and Shukla[13] on February 4, 1959 at 41° N, at which time the average monthly neutron count rate at Mt. Washington was 1996. The adjusted values are lower than the mean of other observers but not significantly different than Waddington's[3,7] computed "best values".

The flight occurred three weeks after the solar flare of May 4, 1960 so Forbush decrease effects[15] from this disturbance should have become negligible. The results of this flight extend the time period over which flux values can be compared and are consistent with the assumption that solar modulation effects are at least as great for M and H nuclei as for the lighter primary nuclei.

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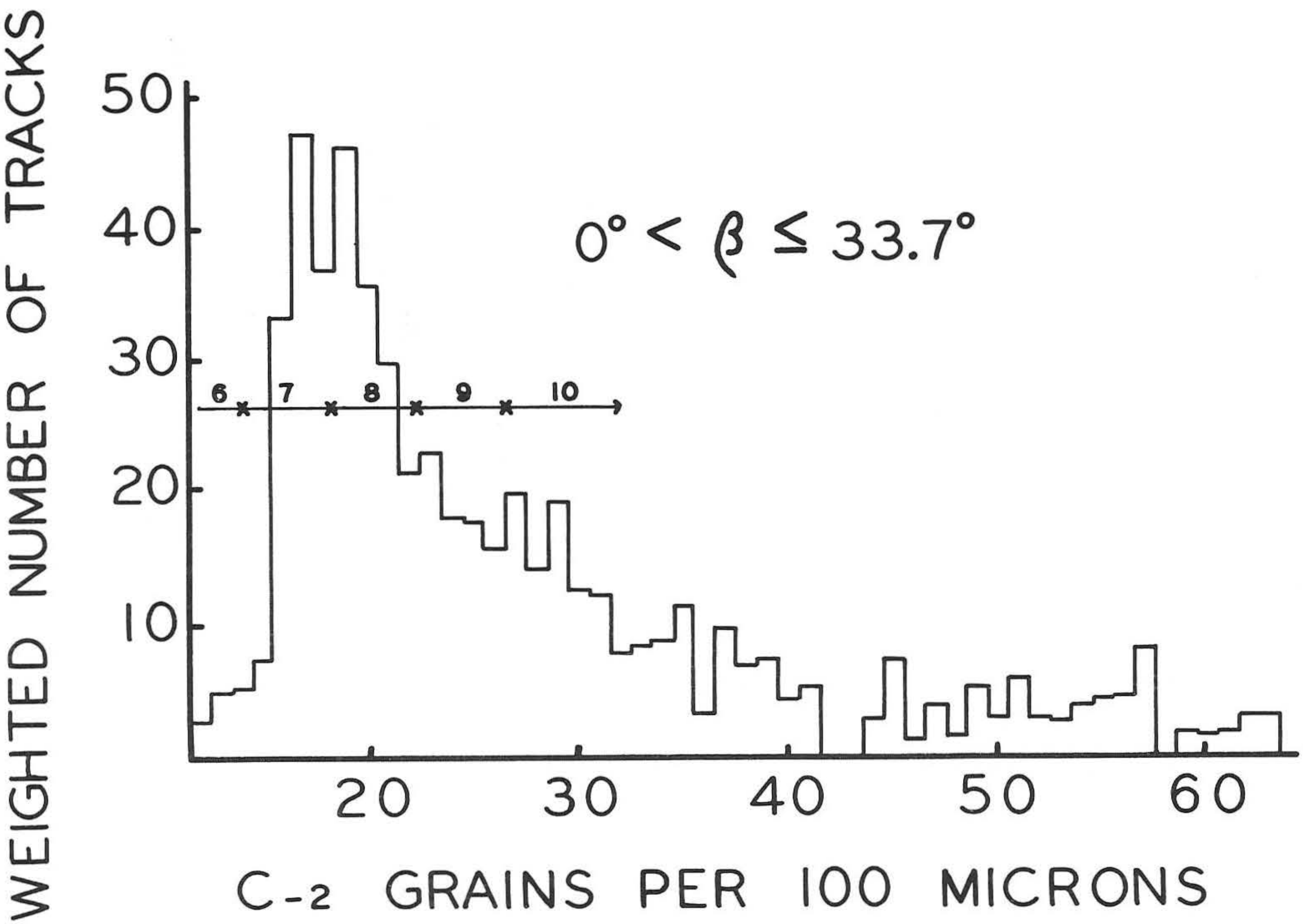
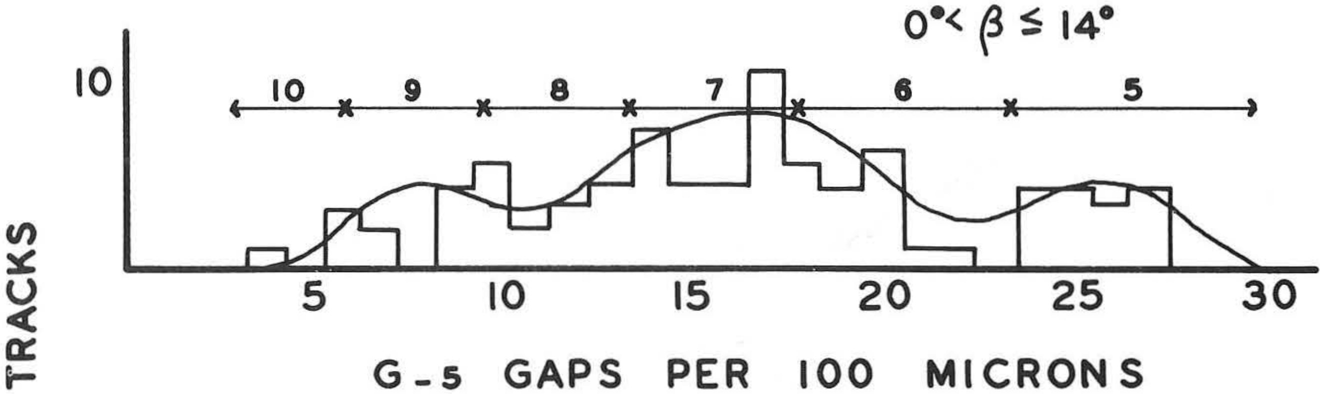
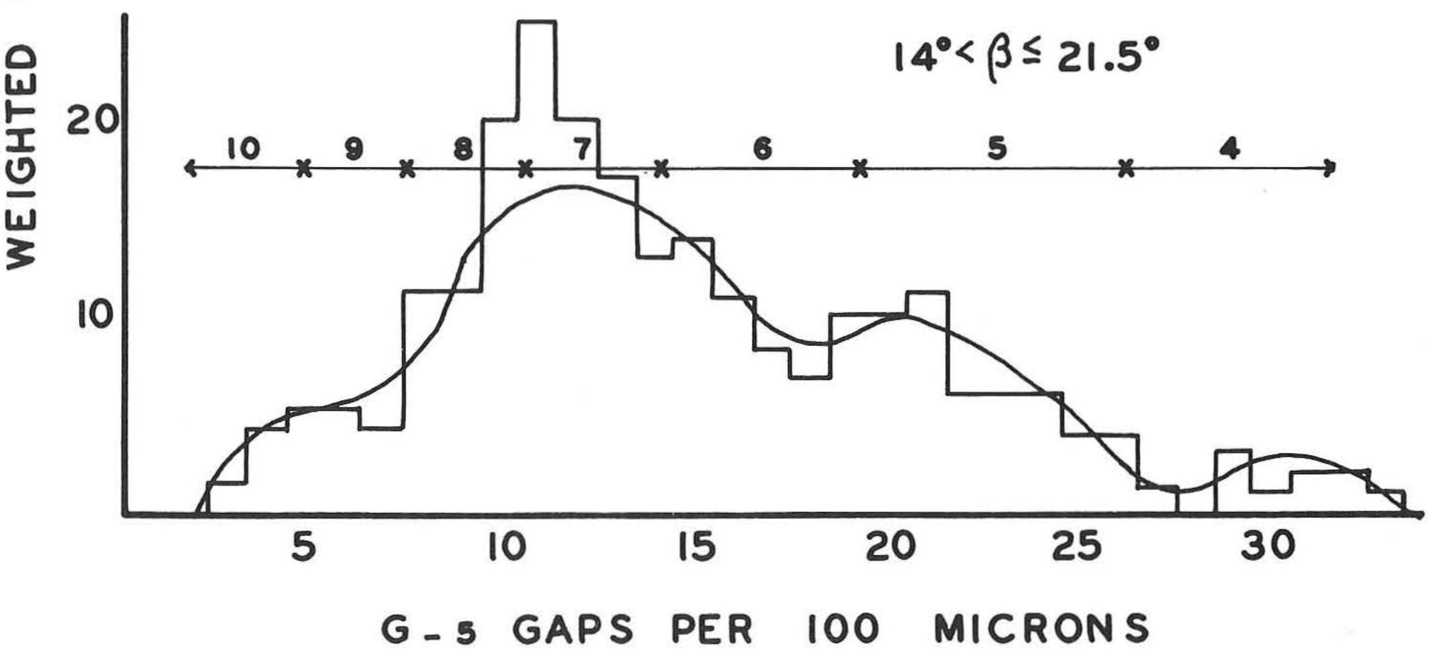
Figures

1. C.2 grain density distribution of heavy nuclei.

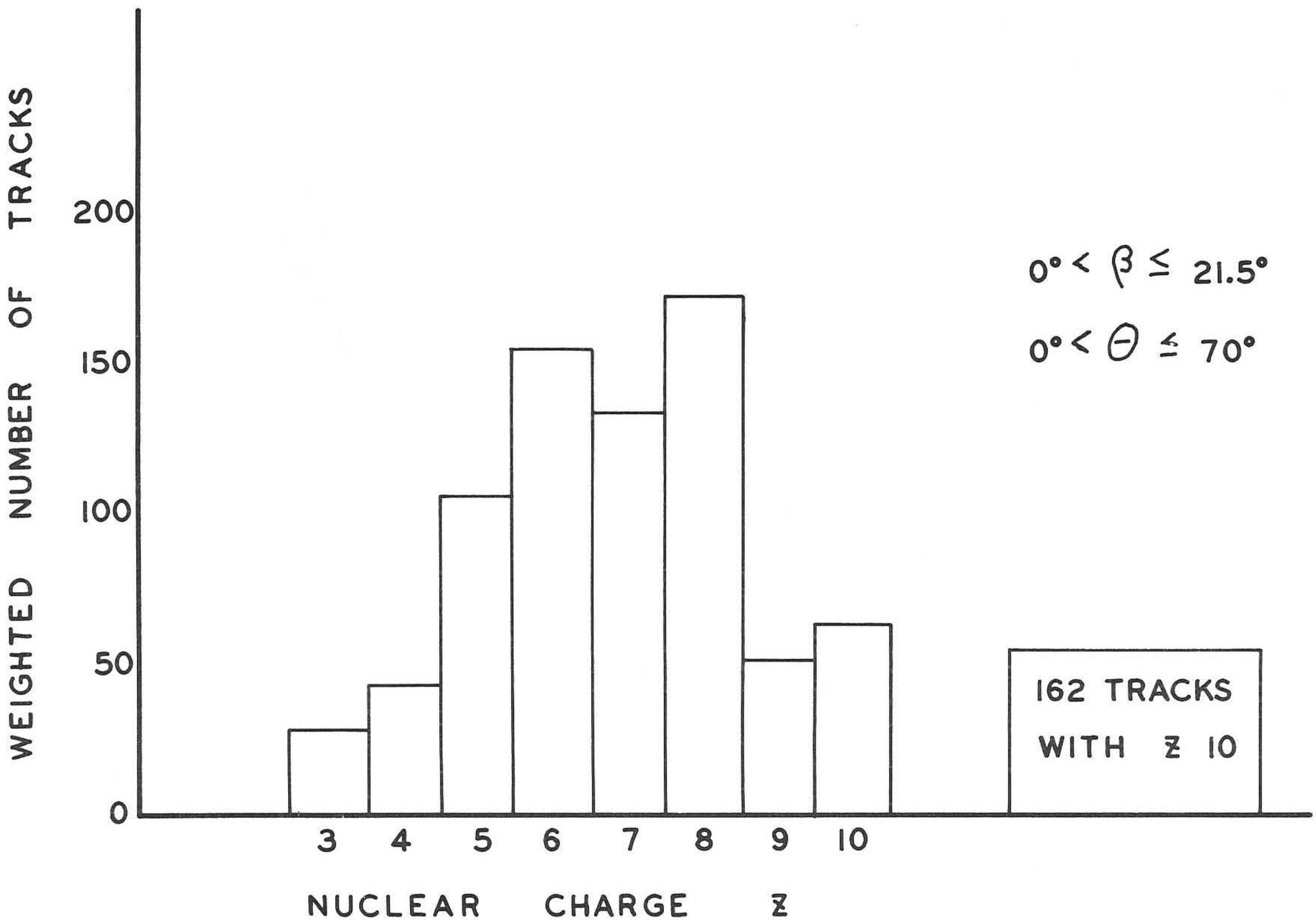

WEIGHTED NUMBER OF TRACKS
50
40
30
20
10
0° < β ≤ 33.7°
6
7
8
9
10
20
30
40
50
60
C-2 GRAINS PER 100 MICRONS

2. G.5 gap density distribution of heavy nuclei at selected dip angles.


0°< β ≤ 14°
10
10
9
8
7
6
5
5
10
15
20
25
30
G-5 GAPS PER 100 MICRONS
WEIGHTED NUMBER OF TRACKS

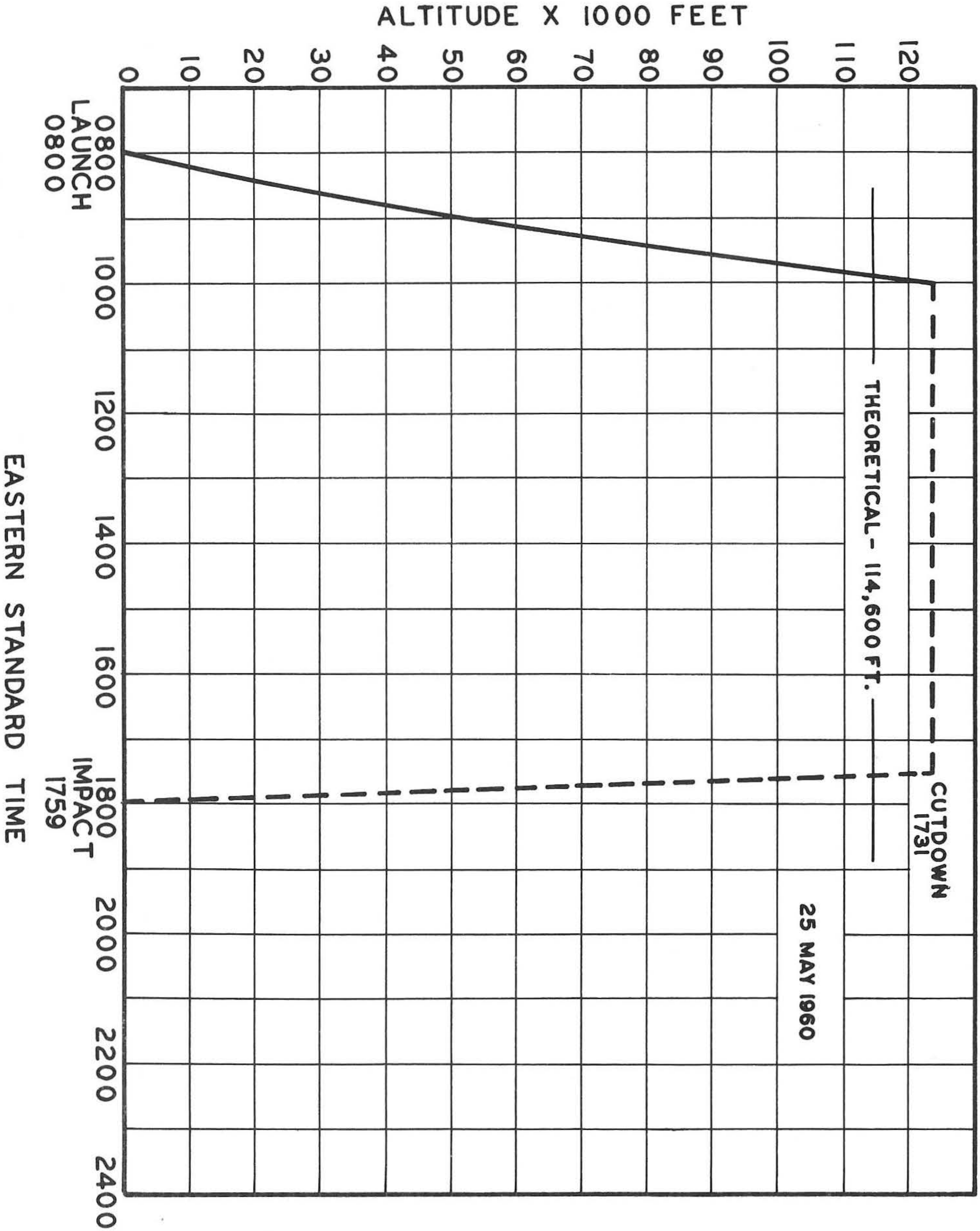

14°< β ≤ 21.5°
20
10
10
9
8
7
6
5
4
5
10
15
20
25
30
G-5 GAPS PER 100 MICRONS

3. Charge distribution of heavy nuclei.



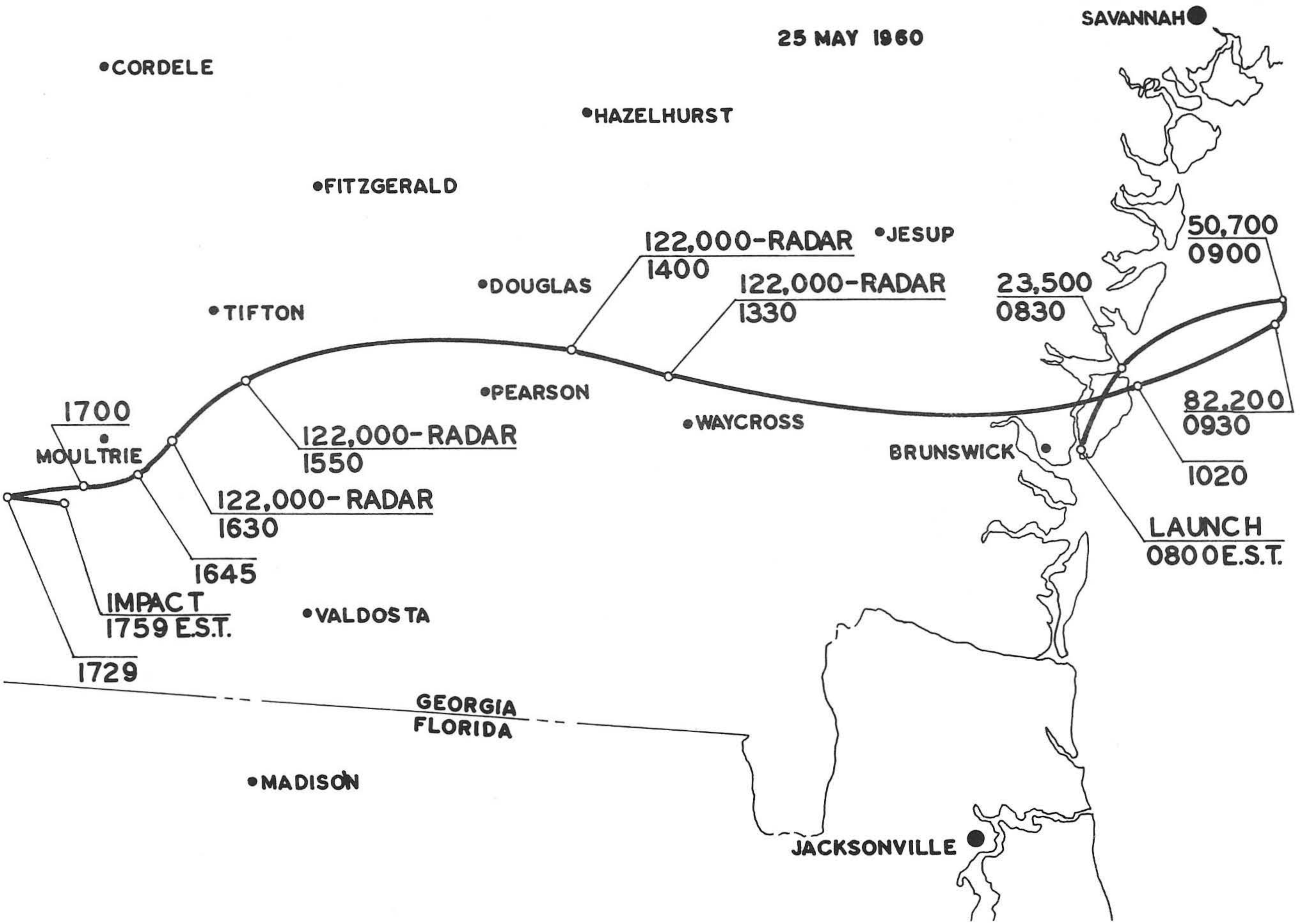
WEIGHTED NUMBER OF TRACKS
0
50
100
150
200
3
4
5
6
7
8
9
10
NUCLEAR CHARGE Z
0° < β ≤ 21.5°
0° < Θ ≤ 70°
162 TRACKS
WITH Z 10

4. Time-altitude record of flight of emulsion stack studied.



ALTITUDE X 1000 FEET
0
10
20
30
40
50
60
70
80
90
100
110
120
EASTERN STANDARD TIME
0800
LAUNCH
0800
1000
1200
1400
1600
1800
IMPACT
1759
2000
2200
2400
THEORETICAL - 114,600 FT.
CUTDOWN
1731
25 MAY 1960

5. Map of flight path of emulsion stack.



25 MAY 1960
SAVANNAH
CORDELE
HAZELHURST
FITZGERALD
JESUP
DOUGLAS
TIFTON
PEARSON
WAYCROSS
BRUNSWICK
MOULTRIE
VALDOSTA
MADISON
JACKSONVILLE
GEORGIA
FLORIDA
LAUNCH 0800 E.S.T.
23,500 0830
50,700 0900
82,200 0930
1020
122,000-RADAR 1330
122,000-RADAR 1400
122,000-RADAR 1550
122,000-RADAR 1630
1645
1700
1729
IMPACT 1759 E.S.T.